Phenomenology of $b \to s\tau\tau$ at a Tera-Z

(and quite some recent progresses)

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Based on arXiv:2012.00665 with Tao Liu
and several ongoing projects

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Outline

- Flavor physics @ Tera-Z factories
- Motivation: B anomalies and LFUV
- Some examples
  - Rare $b \to s\tau\tau$ measurements [Li and Liu, 2020]
  - Rare $b \to s\nu\bar{\nu}$ measurement [In prep.].
  - FCCC $b \to c\tau(\mu)\nu$ measurements [In prep.].
- Summary

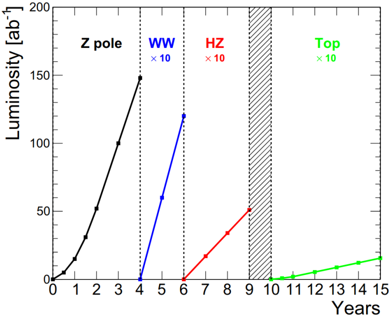
Plan Ahead for the Future Z Factories

Make the best use of data: flavor physics "for free".

		ttbar	Higgs	W	Z
Number of IPs		2			
Hour glass Factor		0.89	0.9	0.9	0.97
Luminosity per IP[1e34/cm^2/s]		0.5	5.0	16	115

Operation mode		ZH	Z	W^+W^-	ttbar (new)
$\sqrt{s}$ [GeV]		~ 240	~ 91.2	~ 160	~ 360
Run time [years]		7	2	1	7.7
CDR	L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	3	32	10	
	$\int L\, dt$ [ab^{-1}, 2 IPs]	5.6	16	2.6	
	Event yields [2 IPs]	1×10^6	7×10^{11}	2×10^7	
Latest	L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	5.0	115	15.4	0.5
	$\int L\, dt$ [ab^{-1}, 2 IPs]	9.3	57.5	4.0	1.0
	Event yields [2 IPs]	1.7×10^6	2.5×10^{12}	3×10^7	3×10^5

CEPC $\sim$ 2.5$\times$Tera-Z



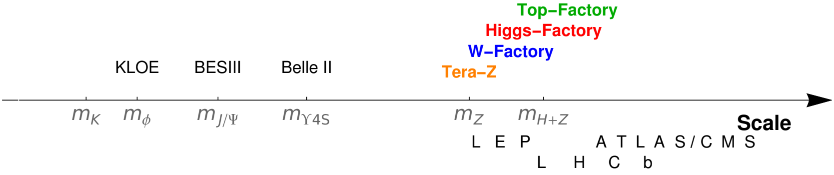
FCC-ee $\sim 7\times$ Tera-Z

Flavor Physics at the Z Pole

Z Factory $\supseteq$ Flavor Factory

Particle-ID $\supseteq$ Flavor-ID!

Channel	Belle II	LHCb	Giga-Z (10^9 Z)	Tera-Z (10^{12} Z)
B^0, $\bar{B}^0$	5.3×10^{10}	$\sim 6 \times 10^{13}$	1.2×10^8	1.2×10^{11}
$B^\pm$	5.6×10^{10}	$\sim 6 \times 10^{13}$	1.2×10^8	1.2×10^{11}
B_s, $\bar{B}_s$	5.7×10^8	$\sim 2 \times 10^{13}$	3.2×10^7	3.2×10^{10}
$B_c^\pm$	-	$\sim 4 \times 10^{11}$	2.2×10^5	2.2×10^8
Λ_b, $\bar{\Lambda}_b$	-	$\sim 2 \times 10^{13}$	1.0×10^7	1.0×10^{10}
c, $\bar{c}$	2.6×10^{11}	$\gtrsim 10^{14}$	2.4×10^8	2.4×10^{11}
τ^+, τ^-	9×10^{10}	-	7.4×10^7	7.4×10^{10}



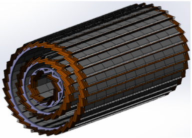
VS. B Factories

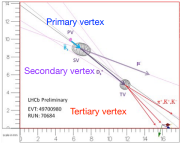
- Much higher b quark boost
- Abundant heavy b hadron

VS. Hadron Colliders

- Clean environment
- Direct missing momenta measurement

Key Detector Features for Flavor Physics



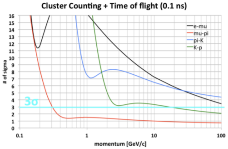


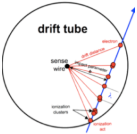
Tracking sys, grants $\mathcal{O}(10)$ fs sensitivity.

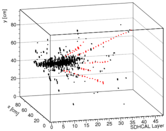
- High time precision for CPV measurements.
- Authentic c/τ reconstruction inside a jet.
- Greater acceptance for displaced signals.

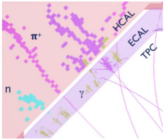
Advanced PID coming from the combination of different methods.

- Flavor tagging for everything.
- Suppressing backgrounds in general.
- Clean leptonic/baryonic modes.









Calorimetry gives neutral energy and angular resolution.

- Better $\not{p}$ measurement for neutrinos.
- Excited states such as D_s^* and radiative decays.
- Distinguishing π^0/η..., allowing h^0X modes.

Vs. Proposed Experiments: How do Golden Modes Look Like?

Multiple charged tracks	Vs. Belle II, low track energy
Multiple short time scales	Vs. Belle II, low track displacement
h^0 or γ (but not too many)	Vs. LHCb, larger noise
e instead of μ ?	Vs. LHCb, relying on MS
ν or other invisible fellas	Vs. LHCb, no sensitivity in principle
Λ or $K_S \to h^+h^-$	Vs. LHCb, low acceptance
Baryonic modes (p or $\Sigma^\pm$?)	Vs. both, advanced PID
Heavy hadrons ($B_s,\ B_c,\ \Lambda_b\ ,\Xi_b$ ...)	Vs. Belle II, imited $\sqrt{s}$
Multi heavy flavor (B_c, exotics...)	Vs. both, unique @ the Z pole
...	...

Many modes with τs in final states fit quite well.

Lepton Flavor Universality (Violation)

Lepton flavor universality (LFU) demands that charged leptons have (almost) identical interactions, only differ by their Yukawa couplings and hence their masses.

However, in both flavor changing neutral current (FCNC) and flavor changing neutral current (FCCC) processes

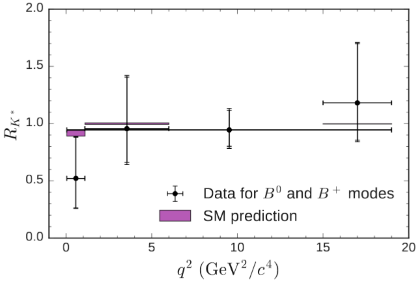
$$R_{K^{(*)}} \equiv \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)} \,, \tag{1}$$

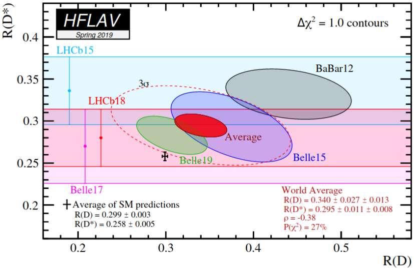
$$R_{D^{(*)}} \equiv \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)} \,, \tag{2}$$

$$R_{J/\psi} \equiv \frac{\mathrm{BR}(B_c \to J/\psi\tau\nu)}{\mathrm{BR}(B_c \to J/\psi\ell\nu)} \,, \tag{3}$$

LFU is challenged.

B Anomalies Indicating LFUV



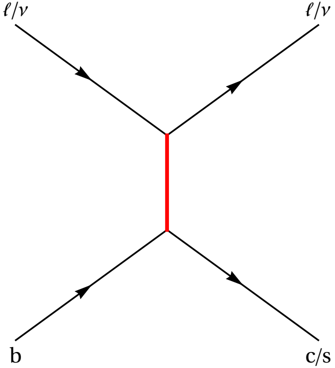


	Experimental	SM Prediction	Comments
R_K	$0.846^{+0.044}_{-0.041}$	1.00 ± 0.01	$m_{\ell\ell} \in [1.0, 6.0]$ GeV^2, via $B^\pm$.
R_{K^*}	$0.69^{+0.12}_{-0.09}$	0.996 ± 0.002	$m_{\ell\ell} \in [1.1, 6.0]$ GeV^2, via B^0.
R_{pK}	$0.86^{+0.14}_{-0.11} \pm 0.05$	~ 1	$m_{\ell\ell} \in [0.1, 6.0]$ GeV^2, via Λ_b.
R_D	0.340 ± 0.030	0.299 ± 0.003	B^0 and $B^\pm$ combined.
R_{D^*}	0.295 ± 0.014	0.258 ± 0.005	B^0 and $B^\pm$ combined.
$R_{J/\psi}$	$0.71 \pm 0.17 \pm 0.18$	0.25-0.28	

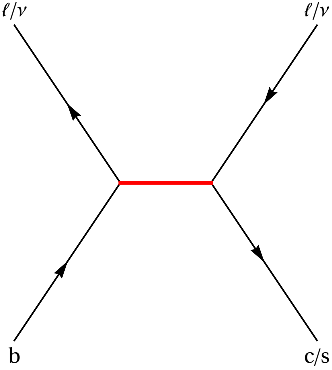
[Tanabashi et al., 2018][Altmannshofer et al., 2018][Aaij et al., 2021][Aaij et al., 2020].

LFUV in BSM: Simplified Models (LO)

Induced by two types of heavy mediators:



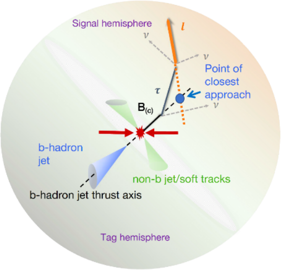
Colorless Mediators



Colored Mediators (Leptoquarks)

See also Andreas Crivellin's talk later!

Pinning Down B Anomalies



Charged current $b \to c\tau\nu$ decays [Zheng et al., 2020, Amhis et al., 2021]. Absolute precision $\sim 10^{-4}$

See Yasmin Amhis' talk in Flavor II session.

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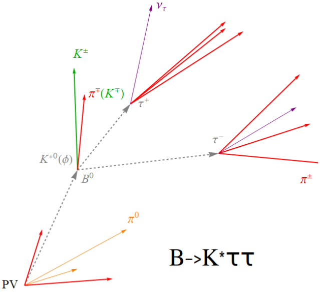
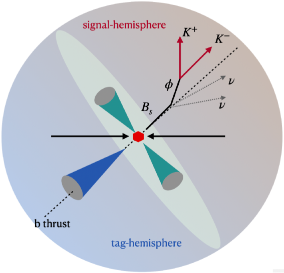


Neutral current $b \to s\tau\tau$ decays [Li and Liu, 2020].

Absolute precision $\lesssim 10^{-6}$: $\sim 10^3 - 10^4$ improvement from current limits.



Neutral current $B_s \to \phi\nu\bar{\nu}$ decay [In preparation]

Not an anomaly yet but closely related

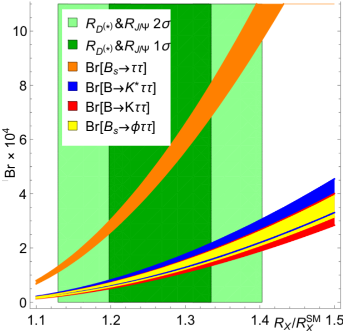
Absolute precision $\sim 10^{-7}$.

Unique opportunities at the Z-pole

LFU Test with $b \to s\tau\tau$ Measurements

Current $b \to c\tau\nu$ anomalies indicate large enhancement of $b \to s\tau\tau$ rates. [Capdevila et al., 2018]

Current experiment constraint on BR $\mathcal{O}(10^{-2.5})$



$$\delta C_9^\tau = -\delta C_{10}^\tau$$

$$= \frac{-2\pi V_{cb}}{\alpha V_{tb} V_{ts}^*}\left(\sqrt{\frac{R_X}{R_X^{\rm SM}}} - 1\right)$$

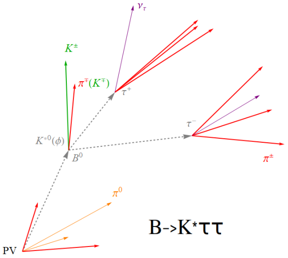
$$\sim \mathcal{O}(10) \times C_{9/10}^{\rm SM}$$

$$O_{9(10)}^\tau = \frac{\alpha}{4\pi}[\bar{s}\gamma^\mu P_L b][\bar{\tau}\gamma_\mu(\gamma^5)\tau]\,,$$

$$O_{9(10)}^{\prime\tau} = \frac{\alpha}{4\pi}[\bar{s}\gamma^\mu P_R b][\bar{\tau}\gamma_\mu(\gamma^5)\tau]\,.$$

From SM ($\mathcal{O}(10^{-7})$) to $\mathcal{O}(10^{-4})$

Overwhelmingly Large SM Backgrounds



Use τ 3-prong decay to locate each vertex

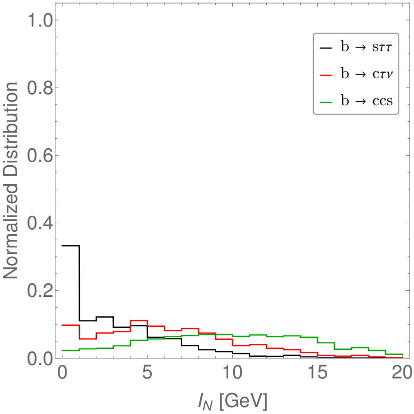
Dominant background from inclusive $D^\pm_{(s)}$ hadronic decays:

	Properties	Decay Mode	BR
$\tau^\pm$	$m = 1.777$ GeV $c\tau = 87.0\ \mu$m	$\pi^\pm\pi^\pm\pi^\mp\nu$ $\pi^\pm\pi^\pm\pi^\mp\pi^0\nu$	9.3% 4.6%
$D_s^\pm$	$m = 1.968$ GeV $c\tau = 151\ \mu$m	$\tau^\pm\nu$ $\pi^\pm\pi^\pm\pi^\mp\pi^0$ $\pi^\pm\pi^\pm\pi^\mp 2\pi^0$ $\pi^\pm\pi^\pm\pi^\mp K_S^0$ $\pi^\pm\pi^\pm\pi^\mp\phi$	5.5% 0.6% 4.6% 0.3% 1.2%
$D^\pm$	$m = 1.870$ GeV $c\tau = 311\ \mu$m	$\tau^\pm\nu$ $\pi^\pm\pi^\pm\pi^\mp\pi^0$ $\pi^\pm\pi^\pm\pi^\mp K_S^0$	$< 0.12\%$ 1.1% 3.0%

Background types	Typical BR
$b \to c\bar{c}s$ (e.g. $B_s \to K^{*0} D_s^{(*)+} D^{(*)-}$)	$\mathcal{O}(10^{-2} - 10^{-3})$
$b \to c\tau\nu$ (e.g. $B^0 \to K^{*0} D_s^{(*)-} \tau^+\nu$)	$\mathcal{O}(10^{-3} - 10^{-5})$
$b \to c\bar{u}d$ (e.g. $B^0 \to D^{(*)-}\pi^+\pi^+\pi^-$)	$\mathcal{O}(10^{-2} - 10^{-3})$

Background overwhelming ($\mathcal{O}(10^5)$ larger before cuts) rather than background free!

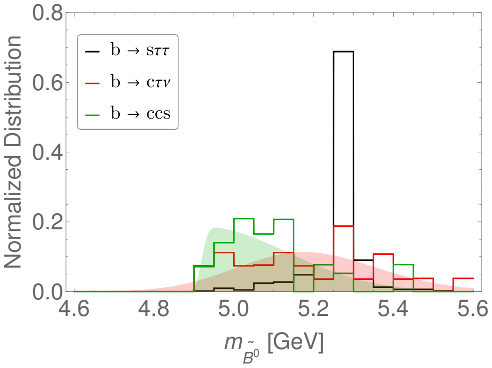
Efforts to Remove Backgrounds



⇐ Good calorimetry saves the day by vetoing extra neutral particles from $D_{(s)}$ decays.

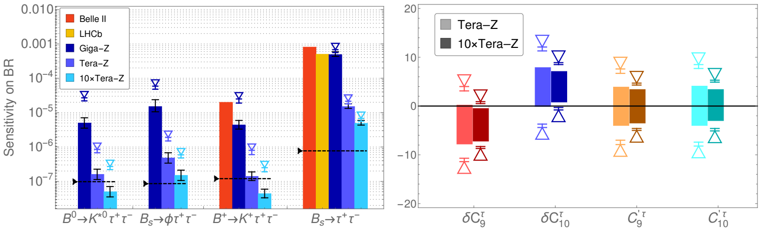
(Potential improvements with "smart" algorithms.)

⇒ Kinmematics of each vertex/track provide B mass peak reconstruction.



Projected Limits

More details in the published work [Li and Liu, 2020]:



- Traditional cut-based analysis: $\mathcal{O}(10^{-5} - 10^{-7})$ precision.
- Still affected by limited detector spacial resolution ("∇" symbols): Motivation for detector R&D!
- EFT-wise way beyond current experimental constraints ($\mathcal{O}(10^3)$).

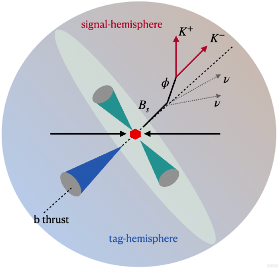
Rare FCNC Decays: $B_s \to \phi\nu\nu$ (Prelim.)

w/ Manqi Ruan, Yudong Wang et al.

$b \to s\nu\nu$ transitions also important for B anomalies. Related with $b \to c\tau(\ell)\nu$ and $b \to s\tau\tau(\ell\ell)$ via gauge invariance.

	Experimental	SM Prediction
BR($B^0 \to K^0\nu\bar{\nu}$)	$< 2.6 \times 10^{-5}$	$(2.17 \pm 0.30) \times 10^{-6}$
BR($B^0 \to K^{*0}\nu\bar{\nu}$)	$< 1.8 \times 10^{-5}$	$(9.48 \pm 1.10) \times 10^{-6}$
BR($B^\pm \to K^\pm\nu\bar{\nu}$)	$< 1.6 \times 10^{-5}$	$(4.68 \pm 0.64) \times 10^{-6}$
BR($B^\pm \to K^{*\pm}\nu\bar{\nu}$)	$< 4.0 \times 10^{-5}$	$(10.22 \pm 1.19) \times 10^{-6}$
BR($B_s \to \phi\nu\bar{\nu}$)	$< 5.4 \times 10^{-3}$	$(9.93 \pm 0.72) \times 10^{-6}$

[Tanabashi et al., 2018, Straub, 2015, Geng and Liu, 2003]



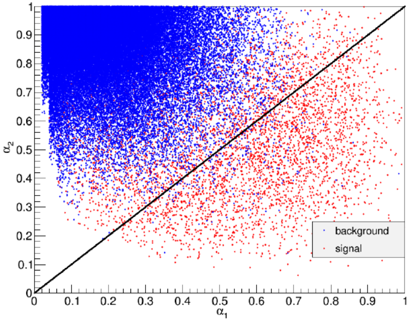
Current limit of this channel still led by LEP: (limited production at B factories, $\vec{p}_\nu$ not achievable at hadron colliders).

Most likely to have a breakthrough at Z factories.

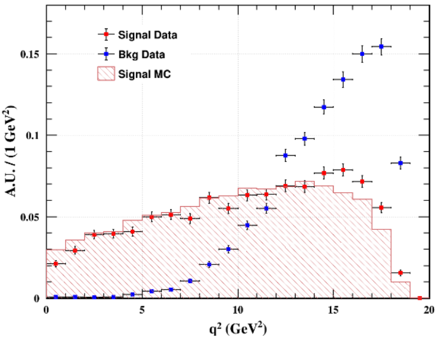
Based on the full simulation of the CEPC.

Rare FCNC Decays: $B_s \to \phi\nu\nu$ (Prelim.)

The dominant background comes from $B \to D^{(*)}\ell(\tau)\nu$, $D^{(*)} \to \phi X$ with no lepton tagged.



Kinematic differences inspired by LEP measurements.

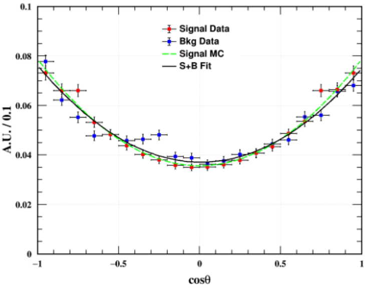


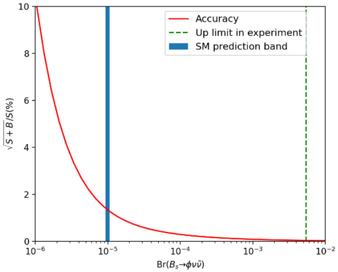
Error of $q^2 \equiv m^2_{\nu\nu} \sim 2.5$ GeV^2 only.

Rare FCNC Decays: $B_s \to \phi\nu\nu$ (Prelim.)

Cuts	$B_s \to \phi\nu\bar{\nu}$	$u\bar{u}+d\bar{d}+s\bar{s}$	$c\bar{c}$	$b\bar{b}$	total bkg	$\sqrt{S+B}/S$ (%)
CEPC events ($10^{12}Z$)	3.03×10^5	4.28×10^{11}	1.20×10^{11}	1.51×10^{11}	6.99×10^{11}	276
$N_{\phi(\to K^+K^-)}>0$	1.24×10^5	1.27×10^{10}	7.23×10^9	8.56×10^9	2.85×10^{10}	136
[a]Signal ϕ	9.00×10^4	1.39×10^9	1.55×10^9	3.14×10^9	6.08×10^9	86.7
Energy asymmetry >8 GeV	7.61×10^4	2.97×10^8	3.61×10^8	9.05×10^8	1.56×10^9	51.9
Energy total <85 GeV	7.36×10^4	6.28×10^7	1.16×10^8	4.65×10^8	6.44×10^8	34.5
$E^N_{B_s}>28$ GeV	6.40×10^4	1.77×10^7	3.03×10^7	8.83×10^7	1.36×10^8	18.2
$\alpha<1.0$	4.34×10^4	6.22×10^6	6.42×10^6	1.00×10^7	2.26×10^7	11.0
b-tag >0.6	3.34×10^4	$<2.0\times10^4$	2.54×10^5	6.44×10^6	6.69×10^6	7.76
$E_\mu<1.2$ GeV and $E_e<1.2$ GeV	3.02×10^4	-	1.08×10^5	2.33×10^6	2.44×10^6	5.20
$(1-\alpha_1)/\theta_\phi^{\text{miss}}<2.0$	2.04×10^4	-	2.82×10^4	4.53×10^5	4.81×10^5	3.47
$q^2<9.0$ GeV	1.27×10^4	-	1.11×10^4	5.48×10^4	6.59×10^4	2.20
BDT response>0.29	1.23×10^4	-	$<2\times10^3$	1.65×10^4	$<1.85\times10^4$	1.43
Efficiency	4.06%	-	$<1.67\times10^{-8}$	1.09×10^{-7}	2.65×10^{-8}	

$\sim 1\%$ relative ($\sim 10^{-7}$ absolute) precision

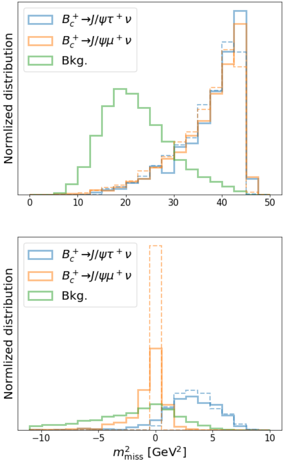




Also able to provide the polarization info of the vector ϕ.

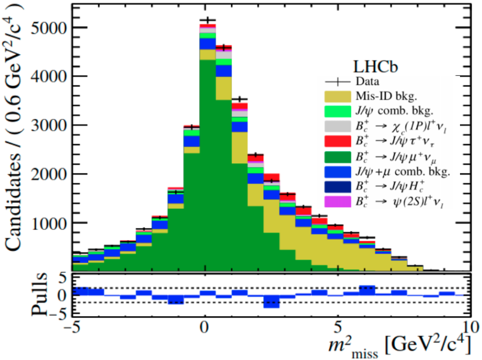
Further LFU Tests with FCCC (Prelim).

w/ Xuhui Jiang, Anson Kwok and Tao Liu et al.



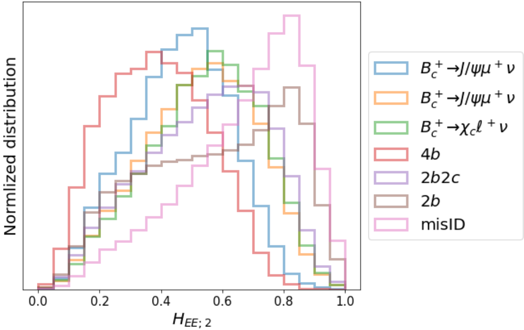
$B_c \to J/\psi\tau(\mu)\nu$ reconstruction

Improved reconstruction quality, also expecting lower combinatoric bkg and mis-ID.



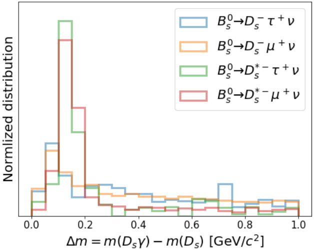
Further LFU Tests with FCCC (Prelim).

B_c are created in double-heavy-flavor ($Z \to b\bar{b}c\bar{c}$) processes.



⇑ Event-shape (here the 2nd FW moment) distributions

Involving event-shapes increases S/B by $\mathcal{O}(10\%)$ when keeping the same statistical significance.



R_{D_s} and $R_{D_s^*}$:

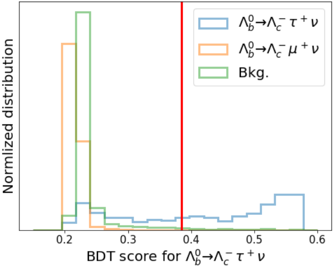
$$R_{D_s^{(*)}} \equiv \frac{\text{BR}(B_s \to D_s^{(*)-} \tau\nu)}{\text{BR}(B_s \to D_s^{(*)-} \ell\nu)} \,. \qquad (4)$$

The key is to separate D_s and D_s^*.
$\sim$ a half of soft photons can be tagged

R_{Λ_c}:

$$R_{\Lambda_c} \equiv \frac{\text{BR}(\Lambda_b \to \Lambda_c \tau\nu)}{\text{BR}(\Lambda_b \to \Lambda_c \ell\nu)} \,. \qquad (5)$$

using the $\Lambda_c \to pK\pi$ decay, clean vertex $\to$ low bkg level.



Further LFU Tests with FCCC (Prelim).

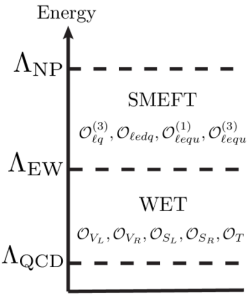
Angles between theoretical sensitivity $\partial_{C_i}\Gamma(b \to c\tau\nu)$ in the 5-D theory space:

θ	$J(\psi)$	D	D^*	D_s	D_s^*	Λ_b	B_c
$J(\psi)$	-	$103°$	$3.01°$	$109°$	$1.96°$	$22.9°$	$81.8°$
D	$103°$	-	$102°$	$6.55°$	$102°$	$82.8°$	$90°$
D^*	$3.01°$	$102°$	-	$107°$	$4.45°$	$20.6°$	$81.2°$
D_s	$109°$	$6.55°$	$107°$	-	$108°$	$88°$	$90°$
D_s^*	$1.96°$	$102°$	$4.45°$	$108°$	-	$23.3°$	$82.8°$
Λ_b	$22.9°$	$82.8°$	$20.6°$	$88°$	$23.3°$	-	$79.6°$
B_c	$81.8°$	$90°$	$81.2°$	$90°$	$82.8°$	$79.6°$	-

Vector (from $R_{J/\psi}$ and $R_{D^*_{(s)}}$), pseudoscalar (from $R_{D_{(s)}}$), baryonic (from R_{Λ_c}) and annihilation (from $B_c \to \tau\nu$, see also [Zheng et al., 2020]) decays are all necessary.

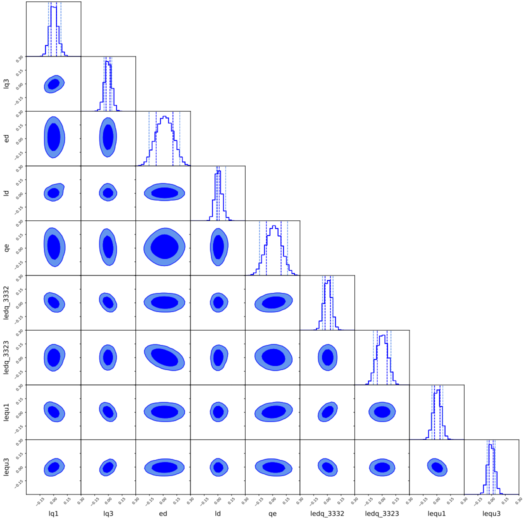
SMEFT Projections (Prelim).

SMEFT Operator	Expansion in Down Basis
$[O_{lq}^{(1)}]_{3332}$	$(\bar{\nu}\gamma^\mu P_L \nu + \bar{\tau}\gamma^\mu P_L \tau)(\bar{b}\gamma_\mu P_L s)$
$[O_{lq}^{(3)}]_{333i}$	$2V_{ci}^*(\bar{\nu}\gamma^\mu P_L \tau)(\bar{b}\gamma_\mu P_L c) - \delta_{i2}(\bar{\nu}\gamma^\mu P_L \nu - \bar{\tau}\gamma^\mu P_L \tau)(\bar{b}\gamma_\mu P_L s)$
$[O_{ed}]_{3332}$	$(\bar{\tau}\gamma^\mu P_R \tau)(\bar{b}\gamma_\mu P_R s)$
$[O_{ld}]_{3332}$	$(\bar{\nu}\gamma^\mu P_L \nu + \bar{\tau}\gamma^\mu P_L \tau)(\bar{b}\gamma_\mu P_R s)$
$[O_{qe}]_{3332}$	$(\bar{\tau}\gamma^\mu P_R \tau)(\bar{b}\gamma_\mu P_L s)$
$[O_{ledq}]_{333i}$	$V_{ci}^*(\bar{\nu} P_R \tau)(\bar{b} P_L c) + \delta_{i2}(\bar{\tau} P_R \tau)(\bar{b} P_L s)$
$[O_{ledq}]_{3323}$	$(\bar{\tau} P_R \tau)(\bar{s} P_L b)$
$[O_{lequ}^{(1)}]_{333i}$	$V_{ci}^*(\bar{\nu} P_R \tau)(\bar{b} P_R c)$
$[O_{lequ}^{(3)}]_{333i}$	$V_{ci}^*(\bar{\nu}\sigma^{\mu\nu} P_R \tau)(\bar{b}\sigma_{\mu\nu} P_R c)$



$$\mathcal{L}^{\rm dim6} \supset \frac{1}{\Lambda_{\rm NP}^2} \sum_{i,j,k,l} \Big([C_{\ell q}^{(1)}]_{ijkl}[O_{\ell q}^{(1)}]_{ijkl} + [C_{\ell q}^{(3)}]_{ijkl}[O_{\ell q}^{(3)}]_{ijkl} + [C_{ed}]_{ijkl}[O_{ed}]_{ijkl} + [C_{\ell d}]_{ijkl}[O_{\ell d}]_{ijkl} + [C_{qe}]_{ijkl}[O_{qe}]_{ijkl} + [C_{\ell edq}]_{ijkl}[O_{\ell edq}]_{ijkl} + [C_{\ell equ}^{(1)}]_{ijkl}[O_{\ell equ}^{(1)}]_{ijkl} + [C_{\ell equ}^{(3)}]_{ijkl}[O_{\ell equ}^{(3)}]_{ijkl} \Big) + \text{h.c.}\ ,$$

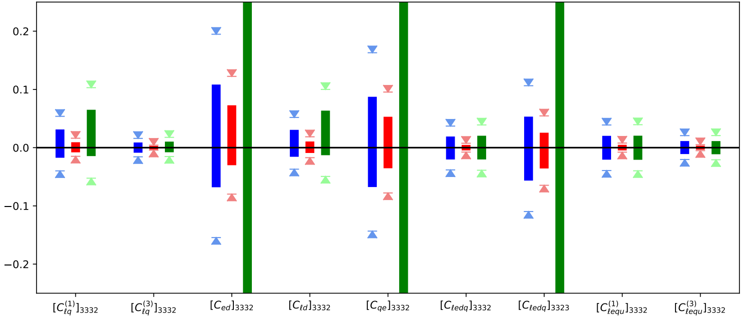
SMEFT Projections (Prelim).



SMEFT Projections from 9 effective channels:($R_{J/\psi}$, R_{D_s}, $R_{D_s^*}$, R_{Λ_c}, $B_c \to \tau\nu$, $B \to K\nu\bar{\nu}$, $B_s \to \phi\nu\bar{\nu}$, $B^0 \to K^*\tau\tau$, $B^+ \to K^+\tau\tau$, $B_s \to \tau\tau$...)

$\Lambda_{\rm NP} = 3$ TeV

SMEFT Projections (Prelim).



$\Uparrow$ Tera-Z, $10\times$Tera-Z, Tera-Z but forgot $b \to s\tau\tau$

(The worst three $\sim \mathcal{O}(0.5)$.)

Probing ~ 10 TeV scale for $\mathcal{O}(1)$ couplings.

Summary

- Flavor physics is related to BSM, SM precision tests, pQCD, lattice, ... everything! Tera-Z is the bridge.
- Flavor studies at the Z-pole benefit from:
  1. Large luminosity (from accelerator physics)
  2. Clean environment and moderate energy (from m_Z)
  3. Good or even revolutionary detectors (from detector R&D)
- New collider/detector at the precision era: new challenges!

- A CEPC flavor physics white paper is ongoing. Contributions from all over the community are necessary.

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